Estimation of Mitral Valve Area in Patients With Mitral Stenosis by the Flow Convergence Region Method: Selection of Aliasing Velocity

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Objectives. We attempted to determine the most suitable aliasing velocity for applying the hemispheric flow convergence equation to calculate the mitral valve area in mitral stenosis using a continuity equation.

Background. The flow convergence region method has been used for calculating mitral valve area in patients with mitral stenosis. However, the effect of varying aliasing velocity on the accuracy of this method has not been investigated fully.

Methods. We studied 42 patients with mitral stenosis using imaging and Doppler echocardiography. Aliasing velocities of 17, 21, 28, 34, 40 and 45 cm/s were used. The transmitral maximal flow rate (Q [ml/s]) was calculated using the hemispheric flow convergence equation $Q = 2 \times \pi \times R^2 \times AV \times \alpha/180$, where R (cm) is the maximal radius of the flow convergence region, AV is the aliasing velocity, and $\alpha/180$ is a factor accounting for the inflow angle (α). Mitral valve area (A [cm^2]) was calculated according to the continuity equation $A = Q/V$, where V (cm/s) is the peak transmitral velocity by the continuous wave Doppler method.

Results. Mitral valve area was progressively underestimated with increasing aliasing velocity. The actual and percent differences noted between the mitral valve area by the flow convergence region method and that by two-dimensional echocardiographic planimetry were -0.06 ± 0.23 cm^2 (mean $\pm$ SD) and $0.09 \pm 15.7\%$ at an aliasing velocity of 21 cm/s, increasing gradually with increasing aliasing velocity, and were -1.24 ± 0.9 cm^2 and $-72.56 \pm 16.4\%$ at an aliasing velocity of 45 cm/s. Mitral valve areas estimated by the flow convergence region method at an aliasing velocity of 21 cm/s in 11 patients with associated >2+ mitral regurgitation (2.12 ± 1.17 cm^2) and 8 with associated >2+ aortic regurgitation (1.28 ± 0.71 cm^2) were not significantly different using planimetry (2.24 ± 1.39 cm^2, $p > 0.05$ and 1.27 ± 0.74 cm^2, $p > 0.05$, respectively) but were significantly different by the pressure half-time method (1.59 ± 1.12 cm^2, $p < 0.001$ and 1.63 ± 0.93 cm^2, $p < 0.01$, respectively).

Conclusions. This study indicated the most appropriate aliasing velocity for the accurate estimation of mitral valve area in patients with mitral stenosis.

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The flow convergence region, a zone of progressive laminar velocity acceleration, can be imaged by color Doppler echocardiography proximal to the restrictive orifice and has been used as a means of calculating maximal flow rate through the regurgitant orifice (1,2). In vitro and in vivo animal studies have demonstrated that this method could be used to calculate the regurgitant maximal flow rate through the orifice (1–6). Recently, the color Doppler flow convergence region method has also been used to calculate the transmitral maximal flow rate and therefore to calculate mitral valve area using the continuity equation in patients with mitral stenosis (7,8). Although it was validated that this method could be applied for the calculation of mitral valve area in mitral stenosis, the way to select the aliasing velocity used in the hemispheric flow convergence equation was not fully investigated in those studies (7,8).

Our recent in vitro study (9) has shown that the shape of the proximal flow convergence isovelocity region is not constant and changes with the aliasing velocity. The selection of an aliasing velocity thus is vital to the accuracy of the color Doppler flow convergence region method for the calculation of flow rate. Therefore, the present study was undertaken to determine the most suitable aliasing velocity for applying the hemispheric flow convergence equation for calculation of the transmitral maximal flow rate. We ascertained the mitral valve area using a continuity equation in patients with mitral stenosis by comparing this method with two-dimensional echocardiographic planimetry and the Doppler pressure half-time method.

Methods

Study patients. The study group consisted of 42 patients (15 men, 27 women with a mean age of 39 years [range 17 to 59 years]) with rheumatic mitral stenosis. The diagnosis was made using imaging and Doppler two-dimensional echocardiography. Twenty-five patients were in sinus rhythm and 17

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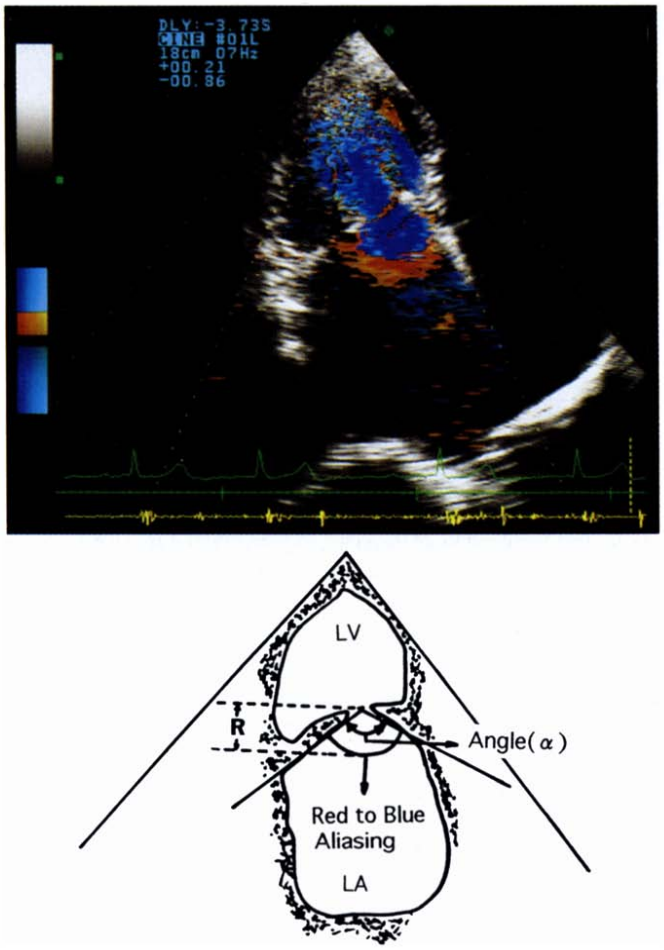


Figure 1. Top, Color Doppler apical long-axis view of the left ventricle in early diastole in a patient with mitral stenosis at the aliasing velocity of 21 cm/s. The flow convergence region is clearly visible and is represented as a heterogeneous **red to blue** aliasing located on the atrial side of the mitral valve, immediately proximal to the mitral orifice. **Bottom,** Schematic diagram showing the radius of the flow convergence region (R) measured as the distance from the first color aliasing of red to blue to the mitral leaflet's edge of the left atrial side along the direction of the ultrasound beam. It also shows the measurement of inflow angle (α) formed by the mitral leaflets. LA = left atrium; LV = left ventricle.

were in atrial fibrillation. The heart rate was 82 beats/min (range 54 to 92 beats/min) for patients with sinus rhythm and 86 beats/min (range 65 to 110/min) for patients with atrial fibrillation. Of 42 patients, 18 had pure mitral stenosis or mitral stenosis associated with ≤2+ mitral or aortic regurgitation, 14 had mitral stenosis associated with >2+ mitral regurgitation and 10 had mitral stenosis associated with >2+ aortic regurgitation measured by color Doppler on a scale of 0+ to 4+.

Two-dimensional echocardiographic examination. The machine used was a two-dimensional color Doppler flow imaging system (Aloka SSD-870) with a transmission frequency of 3.5 MHz. The patients underwent echocardiographic examination in a 30° to 45° left lateral decubitus position. Conventional images were obtained from the parasternal and apical views. The inflow angle formed by the mitral leaflets in early diastole was measured on the apical long-axis view of the left ventricle (Fig. 1).

Standard parasternal short-axis views were used to image the smallest mitral valve area during its maximal opening in early diastole, as described previously (10). Independently, two observers planimetered the inner edges of the mitral orifice using the machine's built-in software. Five consecutive orifice areas on images stored in cine-loop memory were averaged by each observer and the mean results were calculated for each patient. If either observer believed that planimetry could not be performed reliably, the two-dimensional echocardiographic estimation of mitral valve area was judged unsuccessful.

Doppler ultrasound examination. The presence of mitral and aortic regurgitation was sought carefully and semiquantitated by Doppler color flow mapping on a scale of 0+ to 4+ (11,12). The maximal continuous wave Doppler shift and most complete velocity envelope of mitral inflow were recorded by fine adjustment of the direction of the continuous wave beam using both visual spectral display and color Doppler guidance. The angle between the ultrasound beam and the direction of the mitral inflow was minimized to obtain the highest peak velocities. No angle correction was made.

To calculate the mitral valve area using the machine's built-in software, the envelopes of the mitral inflow Doppler spectrum were traced independently by two observers according to the pressure half-time method reported previously (13,14). The peak transmitral velocities also were measured. Five consecutive orifice areas and peak velocities on the Doppler spectrum stored in cine-loop memory were averaged by each observer and the mean results were calculated for each patient. If the leading edges were ambiguous, the Doppler tracing was judged inadequate.

Flow convergence region proximal to the stenotic mitral orifice. The flow convergence region proximal to the stenotic mitral orifice during diastole was observed and recorded in the apical long-axis view of the left ventricle. A color sector angle of 45° was used with a corresponding color flow imaging frame rate of 7 to 15 Hz. A series of aliasing velocities of 17, 21, 28, 34, 40 and 45 cm/s were used by adjusting the zero baseline shift. The maximal radius (R[cm]) of the flow convergence region in a cardiac cycle for each aliasing velocity was selected using the cine-loop function. It was measured as the distance from the first color aliasing of red to blue to the mitral leaflet's edge of the left atrial side along the ultrasound beam, judged by two independent observers (Fig. 1). The shape of the isovelocity surface or shell was assumed to be a hemisphere. The maximal flow rate in diastole (Q [ml/s]) was calculated using the hemispheric flow convergence equation $Q = 2 \times \pi \times R^2 \times AV \times \alpha/180$, where AV was the aliasing velocity (cm/s) used for the recording of the flow convergence region proximal to the mitral orifice and $\alpha/180$ was a factor that accounted for the inflow angle (α) formed by mitral leaflets (7). Five consecutive transmitral maximal flow rates were averaged by each observer and the mean results were calculated for each patient. The mitral valve area (A [cm^2]) was calculated according to the continuity equation $A = Q/V$, where V (cm/s) was the peak transmitral velocity in diastole recorded by continuous wave Doppler.

Reproducibility of measurements. To test reliability of measurements, we randomly selected 10 patients and determined mitral valve area based on the two-dimensional echocardiographic planimetry, Doppler pressure half-time and flow convergence region methods, as judged by one observer on two occasions (intraobserver variability). Another observer independently performed the determination for the same patients (interobserver variability). The observers were blinded to each other's results. The mean and SD of differences between observations were 0.02 ± 0.13 cm^2 (intraobserver) and 0.06 ± 0.18 cm^2 (interobserver) for mitral valve areas determined by two-dimensional echocardiography, 0.03 ± 0.15 cm^2 (intraobserver) and 0.07 ± 0.18 cm^2 (interobserver) for those determined by the Doppler pressure half-time method and 0.02 ± 0.12 cm^2 (intraobserver) and 0.06 ± 0.16 cm^2 (interobserver) for those determined by the flow convergence region method at an aliasing velocity of 21 cm/s.

Statistical analysis. All values were expressed as means ± 1 SD. Mitral valve areas obtained using different methods were compared by analysis of variance for repeated measures. Significant differences between groups were assessed using the Scheffé F test for multiple comparisons. The correlation between mitral valve area obtained using the flow convergence region method at an aliasing velocity of 21 cm/s and those seen with planimetry and the Doppler pressure half-time methods were determined using a linear regression analysis. A p value < 0.05 was statistically significant.

Results

Success rates of two-dimensional echocardiographic planimetry, Doppler pressure half-time method and flow convergence region method for the estimation of mitral valve area. Mitral valve area could be determined in 36 (86%) of 42 patients using two-dimensional echocardiographic planimetry and in 37 (88%) of 42 patients using the pressure half-time method. The flow convergence region was clearly visible and represented as a heterogeneous red to blue aliasing located at the atrial side of the mitral valve, immediately proximal to the mitral orifice, in all 42 patients during diastole at the aliasing velocities of 21, 28, 34, 40 and 45 cm/s (Fig. 1). Although the flow convergence region was visible at the aliasing velocity of 17 cm/s, it was uncertain and subject to great variability among cardiac cycles, deformation and fusion with neighboring flow phenomena and was not used for the analysis. The success rate of the flow convergence region method for the estimation of mitral valve area was 98% (41 of 42). The mitral valve area was not estimated in one patient because of failure in determining the peak transmitral flow velocity using the continuous wave Doppler method.

Actual and percent differences between mitral valve area obtained using the flow convergence region method at different aliasing velocities and that obtained using two-dimensional echocardiographic planimetry. Of 42 patients, 33 had both two-dimensional and Doppler echocardiographic recordings that were satisfactory for measuring the mitral valve area. Of 33 patients, 14 had pure mitral stenosis or mitral stenosis associated with ≤2+ mitral or aortic regurgitation, 11 had mitral stenosis associated with >2+ mitral regurgitation and 8 had mitral stenosis associated with >2+ aortic regurgitation. In this group, two-dimensional echocardiography provided an anatomic standard with which the flow convergence region and Doppler pressure half-time methods could be compared. The actual difference was calculated as mitral valve area seen by the flow convergence region method minus that seen by two-dimensional echocardiographic planimetry. The percent differences were calculated as (actual differences/mitral valve area by planimetry) × 100%. They are shown in Table 1, which indicates that the mitral valve area was progressively underestimated using the flow convergence region method at increasing aliasing velocities, and that the aliasing velocity of 21 cm/s provided the most accurate estimation of mitral valve area when compared with planimetry.

Table 1. Actual and Percent Differences Between Mitral Valve Area Obtained by Flow Convergence Region Method at Different Aliasing Velocities and That Obtained by Two-Dimensional Echocardiographic Planimetry in All 33 Patients

Aliasing Velocity (cm/s)	Actual Difference (cm^2) (mean ± 1 SD)	Percent Difference (mean ± 1 SD)
21	−0.06 ± 0.23	0.09 ± 15.70
28	−0.25 ± 0.49	−11.61 ± 25.07
34	−0.47 ± 0.71	−20.16 ± 24.28
40	−0.93 ± 0.85	−50.40 ± 24.83
45	−1.24 ± 0.90	−72.56 ± 16.40

Flow convergence region method versus two-dimensional echocardiographic planimetry for measurement of mitral valve area. Mitral valve area calculated using the flow convergence region method at the aliasing velocity of 21 cm/s correlated strongly with that measured by two-dimensional echocardiography for all 33 patients studied ($y = 1.1x - 0.12$, $r = 0.98$, SEE = 0.09 cm^2, Fig. 2). There was no statistically significant difference between the mitral valve area obtained using the flow convergence region method at the aliasing velocity of 21 cm/s (1.61 ± 0.92 cm^2) and that measured by two-dimensional echocardiographic planimetry (1.66 ± 1.05 cm^2, $p > 0.05$, Fig. 3) for all 33 patients. There were also no significant differences between the areas obtained by those two methods in patients with associated >2+ mitral or aortic regurgitation. The mitral valve area measured by the flow convergence region method and that seen with two-dimensional echocardiographic planimetry were 2.12 ± 1.17 cm^2 versus 2.24 ± 1.39 cm^2 ($p > 0.05$, Fig. 4) in 11 patients with associated >2+ mitral regurgitation and 1.28 ± 0.71 cm^2 versus 1.27 ± 0.74 cm^2 ($p > 0.05$, Fig. 5) in 8 patients with associated >2+ aortic regurgitation.

Flow convergence method versus pressure half-time method for measurement of mitral valve area. Mitral valve area determined by the flow convergence region method at an aliasing velocity of 21 cm/s also correlated well with that obtained by the pressure half-time method ($y = 0.87x + 0.11$, $r = 0.89$, SEE = 0.17 cm^2, Fig. 6). Although there was no

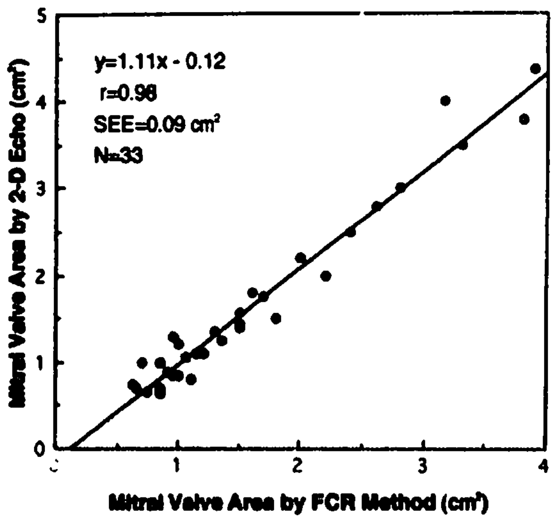
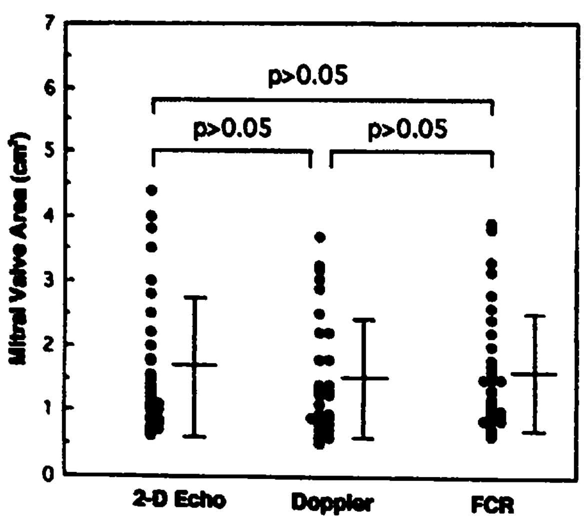


Figure 2. Scatterplot of regression analysis of mitral valve area estimated by the flow convergence region (FCR) method and that determined by two-dimensional echocardiographic planimetry (2-D Echo) in all 33 patients.

statistically significant difference between the mitral valve area determined with the flow convergence region method (1.61 ± 0.92 cm^2) and that measured by the pressure half-time method (1.49 ± 0.89 cm^2, $p > 0.05$, Fig. 3), when all 33 patients were evaluated, this difference became statistically significant when patients with associated >2+ mitral or aortic regurgitation were evaluated separately. The mitral valve area determined by the flow convergence region method (2.12 ± 1.17 cm^2) was significantly larger than that determined using the Doppler pressure half-time method (1.59 ± 1.12 cm^2, $p < 0.001$, Fig. 4) in 11 patients with associated >2+ mitral regurgitation. Mitral valve area measured using the flow convergence region

Figure 3. Scatterplot of mitral valve areas estimated by two-dimensional echocardiographic planimetry (2-D Echo) and the Doppler pressure half-time (Doppler) and flow convergence region (FCR) methods in all 33 patients with mitral stenosis. **Vertical bars** represent mean value ± SD.



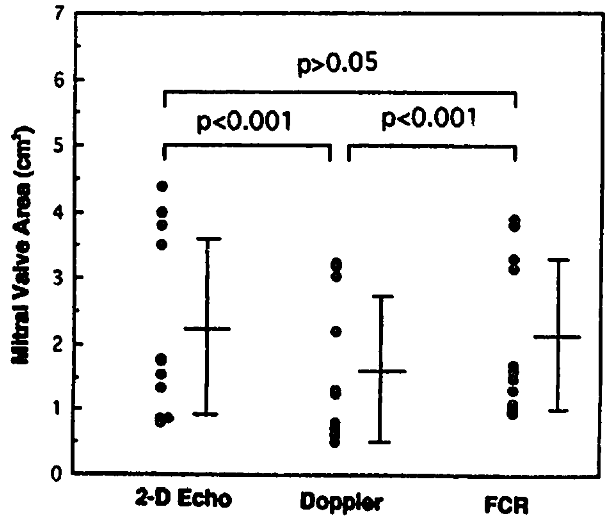


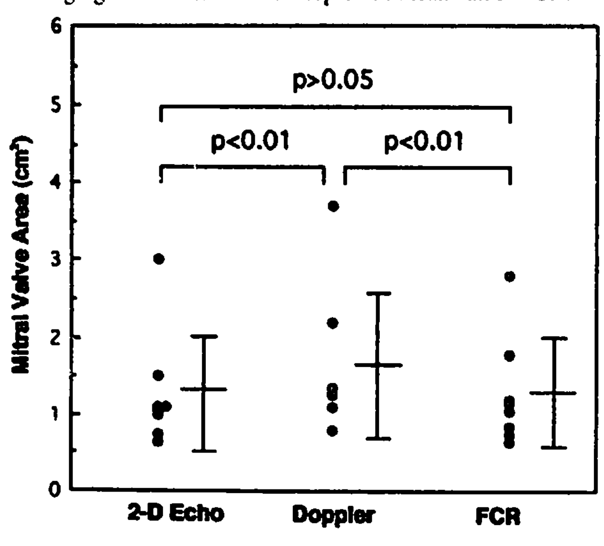
Figure 4. Scatterplot of mitral valve areas estimated by two-dimensional echocardiographic planimetry (2-D Echo) and the Doppler pressure half-time (Doppler) and flow convergence region (FCR) methods in 11 patients with mitral stenosis with associated >2+ mitral regurgitation. **Vertical bars** represent mean value ± SD.

method (1.28 ± 0.71 cm^2) was significantly smaller than that seen using the Doppler pressure half-time method (1.63 ± 0.93 cm^2, $p < 0.01$, Fig. 5) in 8 patients with associated >2+ aortic regurgitation.

Discussion

Selection of aliasing velocities for applying the hemispheric flow convergence equation to calculate mitral valve area using a continuity equation. As indicated in our previous in vitro study (9), the theoretical assumption that the proximal flow

Figure 5. Scatterplot of mitral valve areas estimated by two-dimensional echocardiographic planimetry (2-D Echo) and the Doppler pressure half-time (Doppler) and flow convergence region (FCR) methods in eight patients with mitral stenosis with associated >2+ aortic regurgitation. **Vertical bars** represent mean value ± SD.



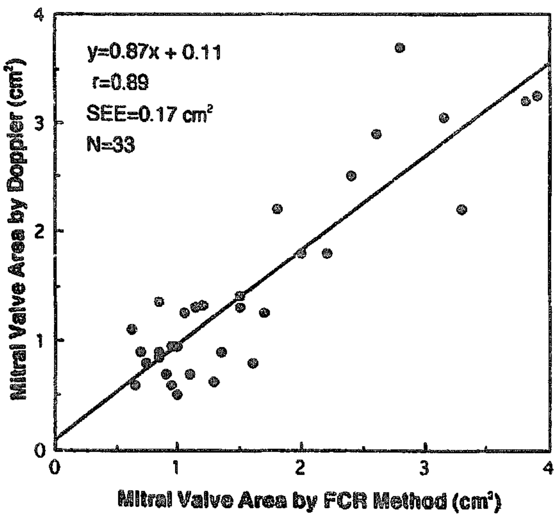


Figure 6. Scatterplot of regression analysis of mitral valve area estimated by the flow convergence region (FCR) and Doppler pressure half-time (Doppler) methods in all 33 patients with mitral stenosis.

convergence region consists of a series of hemispheric surfaces does not always hold. In particular, it does not fit for the practical situation where the shape of the isovelocity surface changes based on the flow rate, orifice size and aliasing velocity, changing from flattened to hemispheric to hemispheroidal shapes such that applying the simple hemispheric flow convergence equation to calculate flow rates will obviously over- or underestimate actual flow rates. Our present clinical study showed that mitral valve area was progressively underestimated by the hemispheric flow convergence equation at increasing aliasing velocities using a continuity equation. This was observed, with actual differences from -0.06 cm^2 at the aliasing velocity of 21 cm/s to -1.24 cm^2 at the aliasing velocity of 45 cm/s when compared with the mitral valve area obtained using two-dimensional echocardiographic planimetry. Because the peak transmitral velocity did not change for a given patient during the period of study, this demonstrated indirectly that the transmitral maximal flow rate in patients with mitral stenosis was progressively underestimated by the hemispheric flow convergence equation at increasing aliasing velocities.

Our recent in vitro study (9) indicated that the over- or underestimation of actual flow rate, in view of the uncertainty of determining true color aliasing shape, could be corrected by selecting the aliasing velocity using the transorifice pressure gradient. This yields an isovelocity surface that fits for the hemispheric assumption, to obtain a more accurate estimation of actual flow rate; the low aliasing velocity should be used for a large orifice and low flow rates that correspond to pressure gradients <40 mm Hg. Previous studies also have shown that the underestimation of actual flow rate is roughly equivalent to the ratio of the aliasing velocity of interest to the peak orifice velocity (15), and the flow rate can be estimated accurately when the aliasing velocity is baseline shifted to <10% of the peak transorifice velocity (16). These observations in part will explain the findings in our present clinical study that the mitral valve area was estimated best using the flow convergence region method at the low aliasing velocity of 21 cm/s. This was seen when compared with the results obtained using planimetry because of the relatively low peak transmitral velocity, from 160 to 250 cm/s, with a corresponding peak pressure gradient from 10 to 25 mm Hg, observed in the present study.

According to our in vitro study (9) and those of others (5,15,16), the appropriate aliasing velocity is different in each hemodynamic state and must be determined for each range of flow conditions encountered clinically. However, in the present study, although the shape and size of the mitral valve orifice was different from patient to patient and actual transmitral maximal flow rates varied (especially between patients without and with various degrees of associated mitral regurgitation), the over- or underestimation of mitral valve area by the hemispheric flow convergence region method at the fixed aliasing velocity of 21 cm/s was not noted even in patients with >2+ mitral regurgitation. This may be explained by findings in our previous in vitro study that the aliasing velocity most suitable for the calculation of flow rate with a hemispheric flow convergence equation was dependent on the pressure gradient, but not on the orifice size (9). This is supported also by findings in the present study that the peak transmitral pressure gradient was within the small range of 10 to 25 mm Hg. Previous studies also have shown that a low aliasing velocity could reduce the effects of the shape and size of the orifice, as well as actual flow rate, on the shape of the isovelocity surface of the flow convergence region (1,2). In addition, a low aliasing velocity allows an increase in the radial distance of the flow convergence region and thereby reduces the error in measuring the radius of the flow convergence region. More recently, Utsunomiya et al. (5) reported in an in vitro study that the shape of the flow convergence region was nearly hemispheric. They noted also that the flow rate was calculated accurately using a hemispheric model with one blue-red interface radius to measure the proximal isovelocity surface area with an aliasing velocity of 15 cm/s under the conditions of a transorifice flow velocity of 1.5 to 2.2 m/s over a range of orifice areas of 0.3 to 2.0 cm^2. This was approximately similar to the conditions encountered in the present study in patients with mitral stenosis.

Estimation of mitral valve area using the flow convergence region, two-dimensional echocardiographic planimetry and Doppler pressure half-time methods. The flow convergence region was visible proximal to the stenotic mitral orifice in all 42 patients with mitral stenosis, including those without satisfactory two-dimensional echocardiography recordings of the mitral valve, whereas the success rates of the two-dimensional echocardiography and Doppler pressure half-time methods for the estimation of mitral valve area were only 86% and 88%, respectively. This indicates that the recording of the flow convergence region proximal to the stenotic mitral orifice was not influenced by the mitral leaflet calcification, thickening and distortion. Thus the flow convergence region method is clinically feasible for the measurement of mitral valve area in patients with mitral stenosis.

The mitral valve area determined using the flow convergence region method at an aliasing velocity of 21 cm/s correlated well with that determined using two-dimensional echocardiographic planimetry; there was no significant difference between them in patients without and with associated mitral or aortic regurgitation. Nevertheless, a statistically significant difference existed both between the mitral valve area determined using the flow convergence region method and that determined using the Doppler pressure half-time method, and between the mitral valve area imaged using two-dimensional echocardiographic planimetry and that seen with the Doppler pressure half-time method in patients with >2+ mitral or aortic regurgitation. This indicates that the flow convergence region method for estimating mitral valve area is accurate and not influenced by associated mitral or aortic regurgitation. It is preferable to the Doppler pressure half-time method in patients with associated moderate to severe mitral or aortic regurgitation.

The mitral valve area evaluated using the flow convergence region method was obtained by dividing the diastolic transmitral maximal flow rate by the diastolic peak transmitral velocity recorded with continuous wave Doppler according to the continuity principle. Therefore, it is actually the effective mitral valve area that corresponds to the area of the *vena contracta*, but not to the anatomic mitral valve area (17). The effective mitral valve area is smaller than the anatomic one owing to the contraction of the flow stream as blood passes through the stenotic mitral orifice (17,18). In the present study, however, there were no significant differences between the mitral valve area seen using the flow convergence region method (effective) at an aliasing velocity of 21 cm/s and that observed with two-dimensional echocardiographic planimetry (anatomic). A potential explanation for this is that the use of an aliasing velocity of 21 cm/s caused a mild overestimation of the transmitral maximal flow rate and therefore an overestimation of the predicted area.

Clinical implications. The present study shows the actual and percent differences between the mitral valve area obtained using the flow convergence region method at different aliasing velocities and that obtained with two-dimensional echocardiographic planimetry. This may provide a way to select the appropriate aliasing velocity to make the flow convergence region isovelocity surface fit the hemispheric assumption, to obtain a more accurate estimation of the transmitral maximal flow rate and therefore the mitral valve area using the continuity principle in patients with mitral stenosis.

As indicated in the present and previous studies (7,8), this technique may provide a simple and useful alternative to calculating the orifice area in mitral stenosis when the pressure half-time is affected by hemodynamic changes (19,20) and direct two-dimensional echocardiographic planimetry is limited (21–24).

Limitations of the present study and the flow convergence region method. The comparisons of mitral valve area estimations among different methods were done only in a limited number of patients (33/42), in which all of the recordings were successful. The accuracy of the flow convergence region method for the estimation of mitral valve area was not determined in patients with unsuccessful echocardiographic planimetry. Further studies are needed to determine the accuracy of the flow convergence method in such a subgroup of patients by using the Gorlin formula for mitral valve area calculation. However, it should be kept in mind that the Gorlin formula for calculation of mitral valve area has its own limitations and is affected by hemodynamic changes, such as associated mitral regurgitation (25).

The angle formed by the mitral leaflets is three dimensional and leaflet geometry may not be evaluated by just measuring the angle created by the leaflet in the apical long-axis view of the left ventricle, as performed in the present study (26). This constitutes one of the limitations of the flow convergence region method for the calculation of mitral valve area.

Another limitation is the small size of the proximal flow convergence region, which may limit the accuracy of measurement. As indicated in the present and previous studies (5,7), such error can be minimized by decreasing the aliasing velocity to increase the measured radius.

Conclusions. The present study presented the actual and percent differences between mitral valve areas obtained using the flow convergence region method at different aliasing velocities and those obtained by two-dimensional echocardiographic planimetry. This provides a way to select the appropriate aliasing velocity so that the flow convergence isovelocity fit for the hemispheric flow convergence equation will obtain a more accurate estimation of the transmitral maximal flow rate, and therefore mitral valve area, using the continuity principle in mitral stenosis. The flow convergence region method allows for accurate measurement of the mitral valve area and is not influenced by associated mitral or aortic regurgitation.

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